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EXPERIMENTAL OBSERVATIONS OF THE TWO-DIMENSIONAL,
POWER-AUGMENTED RAM WING OPERATED
STATICALLY OVER WATER

by

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Experiments were performed in a rectangular tank, partially filled with water and spanned by a flat-bottomed airfoil section, derived from an NACA 0015 thickness distribution. Upstream of the airfoil was placed a two-dimensional air jet, also spanning the tank. One side of the tank was transparent, to permit flow visualization. Two-dimensional turbulent jet theory was used to establish the relationship between the jet exit dynamic pressure and the pressure recovery under the wing, which was supported by experimental evidence.

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It was found that the recovery of pressure was not highly sensitive to jet geometry; however, the formation of spray was. For minimum spray formation, a jet impingement angle of about 25 deg, was established. Several interesting wind-wave flow instabilities were observed. A thrust-reversal phenomenon, predicted by inviscid theory, could not be duplicated in the present experiment.

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ABSTRACT

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ADMINISTRATIVE INFORMATION

INTRODUCTION

This report describes experimental observations made in connection with a larger comprehensive investigation, currently underway, aimed at the determination of the significant parameters governing the behavior of the power-augmented ram wing. In the present study, an attempt has been made to discover and to classify various phenomena having to do with this concept while in the static mode, in the presence of a free-water surface.

The power-augmented ram wing (PARW) is a wing designed to operate in ground effect, whose lift is enhanced by using the airflow of a thruster

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to create a high-pressure region under the wing. Optimally, such a device should be designed to produce the maximum lift augmentation, in a variety of operating conditions, with the minimum sacrifice of propulsive thrust.

Prior to, or concurrent with, this study, investigations have been conducted with a PARW in a wind tunnel over a solid ground plane (report in preparation), a wind tunnel study using the image method (Reference 1), and over-water dynamic tests of the PARW using a towed model. In addition, several theoretical studies have appeared (References 2 and 3). The present study is intended to elucidate some of the phenomena that can be observed only when the ground plane is a free surface, i.e., water. Within the scope of this study, only the static case was considered, corresponding to the PARW lift-off phase. A question may logically arise as to the relevance of such observations and conclusions, whatever form they might take, to the more important case of relative motion between the wing and the free surface. Suffice it to say that the answer to this question is not easily determined without additional study; hopefully, the results of the towed model tests, conducted concurrently with those described herein, will provide information which will permit a unified body of knowledge to emerge.

APPARATUS

The design of the apparatus was undertaken with the following goals:

a) The apparatus was to offer the greatest opportunity for flow visualization.

b) Large amounts of flexibility in experimental parameter variation was to be afforded, without the requirement to make major modifications to the apparatus.

c) Insofar as possible, strict adherence to two-dimensionality was to be maintained.

The major components and their relative arrangement are shown in Figure 1. A brief description of each follows:

Tank - The tank was constructed of plywood and plexiglass. The ends of the tank were made lower than the sides to permit the airflow to pass through the tank with relative unobstruction.

Airfoil - This was built of wood and was extensively pressure-tapped. The airfoil section was an NACA 0015 thickness distribution, cambered so that the bottom surface was flat from the leading edge radius rearward. This is the same section used in the previously referenced studies. The airfoil had a flap, which was extendable through 40°. When placed in service, the angle of attack of the airfoil could be varied from -4° to 20°, measured with respect to the water surface.

Air Supply and Plenum - Air was supplied to the plenum through a 6 inch (0.15m) flexible hose by a 4,800 cfm (2.26 m^3/s) centrifugal fan. The plenum was constructed with internal baffling which produced a turbulent but highly two-dimensional jet. The jet thickness was variable from 0 to 4 inches (0.1 m) by adjustable flaps.

PARAMETERS

Figure 2 shows the number of parameters which could be varied in the experiment. It was evident from the outset that a comprehensive investigation of the effect of varying each individual parameter over the range of interest was out of the question. In addition, it was found early in

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the study that only a few parameters had any real effect on flow phenomena unique to the fluid-air interface (such as a spray generation); it was decided to concentrate efforts in these more promising areas.

Preliminary experiments with varying jet openings also revealed difficulties which could be traced to the characteristics of a constant-speed centrifugal blower. At the widest jet opening 4 inches (0.10m), the jet velocity was not sufficient to produce spray. By narrowing the opening, the jet velocity could be increased, but only at the expense of mass flow since the fan is not a positive displacement device. At a jet opening of approximately 2 inches (0.05 m), dynamic pressure sufficient to generate spray was developed but not on a very repeatable basis. At 1 inch (2.54 cm), results indicated that a steady, reasonably high pressure jet could be counted on; at openings less than this, the mass flow was so restricted that no interesting phenomena could be generated. Thus, all the results reported here correspond to a jet opening of 1 inch (2.54 cm), which may appear restrictive, but which, in fact, was actually not, due to the rapid rate of jet spreading. This effect is discussed subsequently.

As was mentioned previously, the airfoil was generously pressure-tapped in anticipation of pressure distribution measurements. However, it rapidly developed that even the smallest amounts of spray were sufficient to clog the pressure taps - both those on top, through the action of gravity, and those on the bottom, through capillary action. After numerous unsuccessful attempts to unclog all 26 pressure taps simultaneously with compressed air, it was decided that whatever information might be obtained from pressure

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measurements would be, at best, unreliable and, at worst, misleading; further attempts were abandoned. Given sufficient time and ingenuity, this problem probably could have been overcome; but the scope of this investigation did not permit further pursuit of this troublesome aspect.

TWO-DIMENSIONAL TURBULENT JET DYNAMICS AND UNDER-WING PRESSURE RECOVERY

The steady-state solution for the two-dimensional incompressible turbulent jet is given in Reference 4. According to this theory (which experiments adequately support), the longitudinal velocity profile is found to be:

$$u = \frac{\sqrt{3}}{2} \sqrt{\frac{J\sigma}{\rho x}} (1 - \tanh^2 \eta)$$

where J is the total (constant) jet momentum per unit depth, i.e.,

$$J = \rho \int_{-\infty}^{\infty} u^2 \, dy$$

and η is a similarity parameter equal to $\sigma y/x$. Here x and y are the longitudinal and cross-stream coordinates of the jet measured from the jet centerline, ρ is the density of the jet medium, and σ is an experimentally determined constant found to be 7.67. Calculating J, according to the above expression, yields the result

$$J = \frac{4}{3} \rho U_s^2 \, s/\sigma$$

where U_s is the centerline velocity measured at a downstream distance s.

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Then at any streamwise station, it results that

$$\frac{u}{u}\text{ max} = 1 - \tanh^2\eta$$

where $u_{max} = u(y = \eta = 0)$.

From this it can be calculated that at $\eta = 3$, $u/u_{max} \approx 1$ percent. Defining this value of η as a nondimensional jet half-width, say η_0, then

$$\eta_0 = \frac{\sigma w}{2x} = 3$$

where w is the sensible jet width. Then the spreading rate of the jet is calculated to be

$$\frac{dw}{dx} = 6/\sigma \approx 0.78.$$

The two-dimensional turbulent jet spreads very rapidly indeed; the sensible boundary between the jet and the surrounding air forms a vertex angle of about 42°, regardless of the jet velocity, fluid viscosity, or other parameters which intuition might suggest as factors.

As regards the present experiment, the first implication of this result is that for a jet aligned with the center of the gap between the wing leading edge and the water, some spillage of the jet over the upper surface of the wing may be expected, even in the absence of a downstream constriction, i.e., a deflected flap, for $x_j > 1.2$ h.

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The second useful result to emerge from this analysis is that it provides the means for calculating the maximum underwing pressure recovery available from a given jet. The procedure is as follows:

Since the experiment is conducted at ambient conditions, the maximum pressure recovery that can be expected under the wing is the mean jet dynamic pressure attained when the flow is stagnated beneath the wing. This can be effected by lowering the flap so that the trailing edge is at, or preferably beneath, the water surface. The pressure recovery can then be measured simply by noting the distance that the water level depresses beneath the wing, say Δh.

The mean jet dynamic pressure can, in turn, be calculated from the previous results, i.e.,

$$\bar{q} = \frac{1}{w} \int_{-w/2}^{w/2} \rho \frac{u^2}{2} \, dy$$

$$= J/2w = \frac{4}{3} \left(\frac{\rho U_s^2}{2} \right) \left(\frac{s}{\sigma w} \right)$$

from above. Now, if a pitot-static tube is placed at the jet centerline in the plane of the jet exit, then $q_s = \frac{1}{2} \rho U_s^2$ can be determined. Using the spreading angle of 42° previously established, the virtual jet origin can be determined so that at the plane of the jet exit $s = (t_j/2) \cot (38^\circ/2)$: thus, $s/w = 1.45$ since $w = t_j$. Then

$$\bar{q} = \frac{4}{3} \left(\frac{1.45}{7.67} \right) q_s = 0.252 q_s \simeq q_s/4.$$

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It is evident that the maximum Δh that may be expected is about $q_s/4$, which will occur when the bulk of the jet efflux is "captured" by the leading edge gap.*

The results shown in Figure 3 appear to bear out this conclusion. It may be noted that the requirement for x, to be approximately equal to h to effect full pressure recovery, appears to be overly restrictive. This is no doubt because the major contribution to the dynamic pressure integral is concentrated in a central core which is much thinner than the jet itself.

Considering the fact that the analysis is based on a freely expanding jet in the absence of solid boundaries (which does not correspond to the present physical set-up here), the agreement between the predicted and observed pressure recovery is a great deal better than might have been expected.

The result of this development appears thus to be threefold:

(1) The maximum pressure recovery that can be expected beneath the wing is one-fourth the maximum dynamic pressure of the jet, measured at its exit plane.

(2) The maximum pressure recovery will be achieved for all practical purposes when the axis of the jet is reasonably aligned with the midpoint of the leading edge gap.

(3) To achieve maximum pressure recovery, the jet exit should not be placed more than three or four gap widths upstream.

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*Obviously, if the flow beneath the wing is completely stagnated, the jet efflux must seek another path of egress. However, the stagnation pressure (relative to ambient conditions) will still be the mean jet stagnation pressure in this region.

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SPRAY PRODUCTION

Where relative motion exists between air and water, spray will be formed when the dynamic pressure of the air is greater than about 2 psf (10^{-3}ATM) measured relative to the water;* thus, in all practical air-cushion borne vehicles, one may expect the presence of spray to a greater or lesser degree.

While all spray originates through a viscous interaction between air and water, it is possible (based on direct observation) to loosely categorize spray formation as two rather distinct types: one which results when a jet of air blows roughly parallel with the water surface ("shear spray") and another which forms as a result of a cratering effect when the axis of a jet impinges on a water surface at a substantial angle ("pressure spray"). Figure 4 shows these two types of spray.

In the case of shear spray, the spray is continuously produced over a large area depending, of course, on the dynamic pressure of the jet. (In the present experiment, the region of spray formation was a distance equal to several chord lengths.) Pressure spray, on the other hand, is produced only at the peaks of the crater and thus is a much more localized phenomenon. In addition, shear spray--as it was observed in this experiment--is best described as a mist, i.e., the atomization of water; whereas, pressure spray appears to be composed of larger sized, easily observable droplets that, for the most part, are given lofty trajectories of a scale which exceeded that of the apparatus. It is also important to note that considerable amounts of pressure spray are propelled upstream of the jet, which ought to be an important consideration in the placement of engine inlets in a real application, if spray ingestion were to be avoided.

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*Personal communication with R. W. Gallington, DTNSRDC.

The type of spray which will be produced when a jet impinges on a still water surface is primarily a function of the impingement angle (all other things equal) and, as might be expected intuitively, there is not sharp distinction between the two; however, observations showed that when the jet angle was less than 20°, shear spray was formed, and when greater than about 30°, the spray was, as best could be discerned, of the pressure type.

DEPENDENCE OF SPRAY TYPE ON TRAILING EDGE GAP TO JET WIDTH RATIO

The previous comments should be understood to apply when a free jet impinges on a water surface in the absence of any other disturbing factor. However, when this takes place in the vicinity of the wing, the type of spray appears to depend on the ratio of the trailing edge gap to the jet width.

Referring to Figure 5, it may be seen that when h_f/h is of unit order with $h/t_j > 3$, essentially all the jet efflux passes between the wing and the water surface. In this case, mostly shear spray is formed - a great deal of which, incidentally, impacts the lower surface of the wing; in the present experiments, the wing was fully awash of the lower surface in this configuration.

When the flap was positioned so that the trailing edge height-to-jet width was of unit order, however, the formation of shear spray vanished. In this new configuration, the airflow is essentially stagnated under the wing (as evidenced by an almost completely quiescent water surface, displaced downward by an amount corresponding to the mean dynamic pressure of the jet).

Thus, one can assume here that the maximum velocity at the trailing edge of the airflow is essentially that of the jet; significant amounts of pressure spray are thus created - but downstream of the trailing edge. Evidently, the effect of the wing in this case is to extend the length of the crater (previously discussed) to a streamwise dimension comparable to the length of the chord. With the exception of small amounts of upstream spray, which were randomly lofted into the jet and hence sent downstream, the wing remained essentially dry.

To test the hypothesis that the parameter governing the spray type is the trailing edge gap to jet width ratio, a simple extension (consisting of a piece of sheet metal) was fitted to the flap which increased the flap chord by a factor of two. The water level was lowered accordingly, and the experiment was repeated. Qualitatively, the same phenomena were observed; that is, the shear spray in evidence at large h_f/t_j ratios is essentially suppressed, giving way to a pressure-type spray of h_f/t_j ratios approaching unity.

ANOTHER SPRAY SOURCE - THE BIFURCATED JET

Although the jet used in this study was a two-dimensional (although highly turbulent) jet, there is reason to suppose that in a real application, the jet might consist of several, closely spaced circular jets, which might be the case if a series of jet engines, placed side-by-side, were to be used. Therefore, it was thought necessary (and as it turned out, highly instructive) to investigate the effect of two discrete jets acting in close proximity, as compared with the single two-dimensional jet as originally designed.

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This was achieved by placing an obstruction (actually several pieces of masking tape), equal in width to one jet thickness, at the center of the jet. Quite surprisingly, this configuration, similar in all respects from the previously described one except for this small modification, produced a large amount of whirling spray at the point of water impact - caused by the impingement of the vortices created by the obstruction as they interacted with the free surface. Whether or not this would be observed in a full-scale experiment is a matter of conjecture, but the intensity of the spray formed by this mechanism suggests that the use of discrete jets might well lead to a primary source of troublesome spray which would not be gotten rid of easily. Figure 6 depicts this behavior.

SUBMERGED TRAILING EDGE STUDIES - OBSERVED INSTABILITIES

In order to investigate the boundaries of various flow phenomena, tests were run with the flap trailing edge fully submerged. At depths of submergence (measured statically) equal to or less than the mean total pressure of the jet, the water surface is depressed sufficiently to permit the passage of air between the water and the trailing edge. When the water level was increased to half again this amount, an interesting streamwise flow instability occurred. Figure 7 shows this schematically. In this case, a standing wave developed under the surface which increased in amplitude until the lower surface of the wing was awash and a large amount of spray was generated under the wing. At the opposite extreme, the water crested in front of the wing; the interaction of the jet with this crest caused large amounts of spray to be formed, which was carried by the airflow over the top of the wing.

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Since the wing chord was a fractional multiple of the tank length, there was some reason to suppose that the wave amplification was caused by reinforcing reflections from either end of the tank. However, when the air jet was discontinued, the wave motion quickly subsided and rapidly became reestablished when the jet was turned back on, suggesting the phenomenon was not a result of a tank sloshing mode.

At depths of trailing edge submergence approximating two mean jet total pressures, the longitudinal instability just described gave way to a cross-stream instability, shown in Figure 8. In this case, a cosine-type wave alternately caused venting at the sides and in the middle, generating spray behind the wing. This mode appeared to produce little or no upstream influence.

At depths of trailing edge submergence greater than about 2.5 mean jet dynamic pressures, the trailing edge remained fully submerged and no instabilities took place.

The implications of those observed instabilities vis-à-vis a full-scale craft are not readily apparent. In the first place, it is not evident how such phenomena would scale. In addition, the cross-stream instability was clearly a result of having side walls on the wing. Finally, it should be possible in a full-scale PARW vehicle to have sufficient parametric authority to avoid situations in which the trailing edge flap would ever be fully submerged unless it were seriously overloaded or under-thrusted. However, the observations described here were wholly unanticipated and are therefore worth recording for the sake of completeness.

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THRUST REVERSAL STUDIES

In theoretical treatments, it was found that certain parametric combinations (small t_j/h, small h_f/t_j, small θ_j) caused the wing to act effectively as a thrust reverser (see Figure 9). Since the present experiment did not permit the direct measurement of thrust, it was decided to investigate this through the use of a tuft grid to permit visualization of local flow directions in the vicinity of the leading edge. Consequently, a tufted splitter plate was fitted to the wing which extended a distance of 25 percent C in all principal directions from the leading edge (see Figure 10).

The tuft studies showed that, rather than behaving as a thrust reverser, the system acted more like a fluidic switch; that is, as the h_f/t_j was decreased, a point was reached where the mass flow beneath the wing was substantially restricted, and the flow was essentially stagnated. This, in turn, led to a total rearrangement of the streamlines in the leading edge region, and ever-increasing amounts of the jet efflux passed over top of the wing, as shown in Figure 9.

In accounting for the difference between theory and experiment, it should be noted that the theory describes an inviscid jet which preserves its identity regardless of distance from its point of origin; whereas, experiment was performed with a fully turbulent, spreading jet.

SUMMARY OF OBSERVED EFFECTS OF VARIOUS PARAMETERS

Based upon direct observations, the principal effects of varying the parameters in this study are summarized as follows:

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1. **Trailing edge flap** - At least in the static mode, the flap should not be thought of as a conventional aerodynamic flap, but rather as a trailing edge gate valve that controls the amount of air passing under the wing. In a configuration where the jet centerline is directed towards the center of the leading edge gap, it is the deflection of the flap which determines the level of over pressure under the wing and the type of spray formation which will be present. The significant parameter is not the flap angle *per se*, but rather the ratio of h_f to t_j.

2. **Angle of attack** - There is little effect in the static mode on the previous findings due to angle of attack. The principal effect of angle of attack is merely to increase the capture areas under the wing. For an undeflected flap (a relatively uninteresting case for the static PARW), an angle of attack would produce an accelerating flow under the wing, leading to a positive pitching moment. However, this could not be verified due to the previously discussed difficulty with performing pressure measurements in the presence of spray.

3. **Jet geometry** - All other things equal, the greatest pressure recovery under the wing occurred when the jet axis was aligned with the center of the gap. If the jet axis were placed above this point, air spilled over the wing. If placed below this point, there was a tendency to create a local depression or crater in front of the wing, which led to inefficient pressure recovery under the wing and localized pressure spray formation. The best all-around impingement angle was determiend to be about 25°.

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As was explained previously, the mean dynamic pressure of a two-dimensional turbulent jet remains sensibly constant for a considerable distance downstream, although the jet spreads at a rapid rate in the entrainment process. The effect of moving the jet upstream of the leading edge gap is thus to decrease the total pressure recovery under the wing, although the effect does not appear to be pronounced until the distance-to-gap ratio exceeds about four.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the efforts of the members of the Technical Support Department, Division of Engineering and Weapons, at the U. S. Naval Academy headed by Mr. Larry H. Heisig, many of whom made important contributions to the construction of the apparatus. In particular, the author wishes to thank Mr. Willard Rolloson for his ingenuity and skill in constructing the airfoil section and Mr. Jack Thomas, who assumed the overall responsibility for the construction of the tank. Finally, appreciation is extended to Mrs. Mary Tomanio, who typed the final draft.

REFERENCES

1. Papadales, B. S., Jr., "An Evaluation of a Two-Dimensional Power Augmented Wing in Ground Effect Model Under Static and Dynamic Free-Stream Conditions," DTNSRDC Report ASED-353 (Jun 1976).

2. Gallington, R. W., "Sudden Deceleration of a Free Jet at the Entrance of a Channel," DTNSRDC Report ASED-350 (Jan 1976).

3. Gallington, R. W. and H. R. Chaplin, "Theory of Power Augmented Ram Lift at Zero Forward Speed," DTNSRDC Report ASED-365 (Feb 1976).

4. Schlicting, H., "Boundary Layer Theory," Fourth Edition, McGraw-Hill, New York (1958).

FLEXIBLE HOSE

AIR
SUPPLY

PLENUM

PLEXIGLASS

AIRFOIL

WATER

PLYWOOD
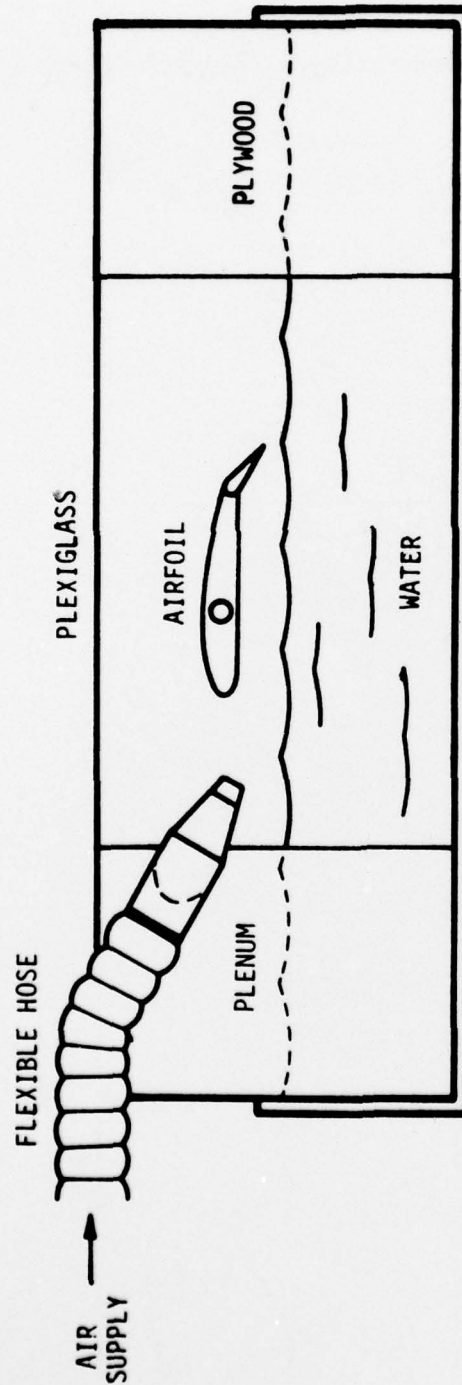
PRINCIPAL DIMENSIONS:

TANK LENGTH - 12 FT (3.6m)   AIRFOIL CHORD - 3 FT (0.9m)

TANK HEIGHT - 4 FT (1.2m)

TANK WIDTH - 2 FT (0.6m)

Figure 1 - Experimental Apparatus and Major Components

Note: All except c and c_f are variables
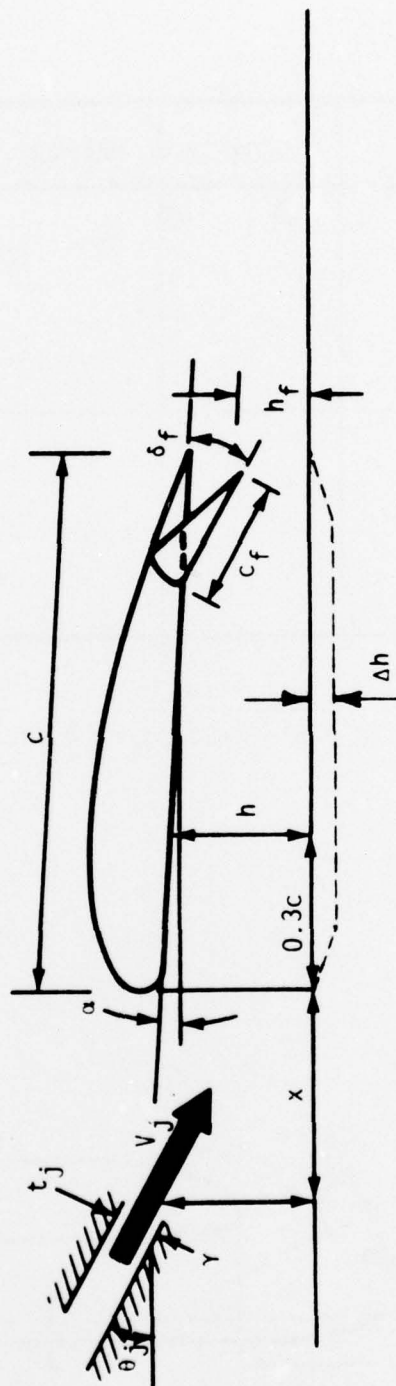
Figure 2 - Parameter Ensemble for Power-Augmented
Ram Wing Experiment

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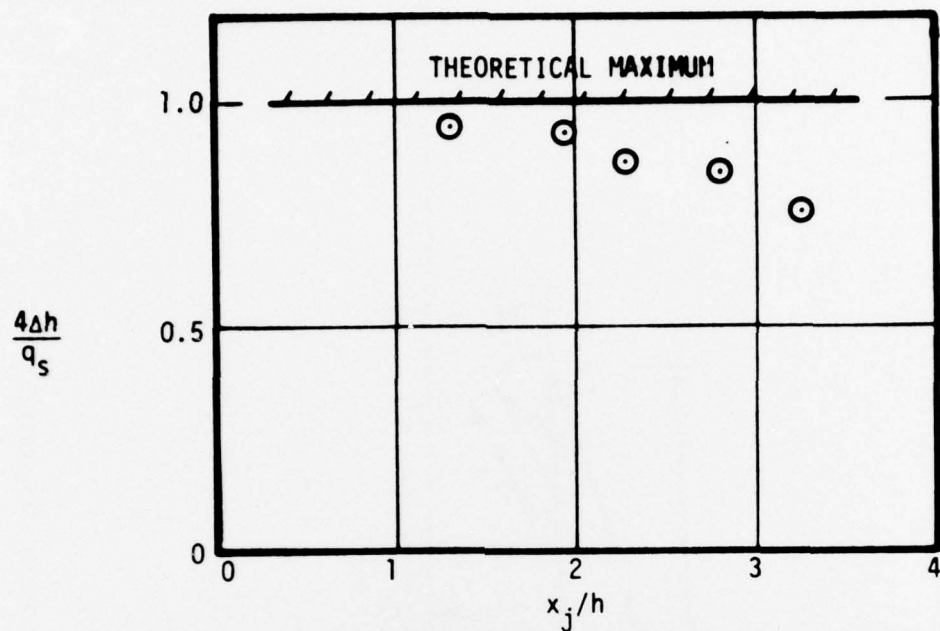
h=4 IN. (10.16 cm), θ_j =25°, α=0°, q_s = 3.4 IN. H_2O (8.64 cm)
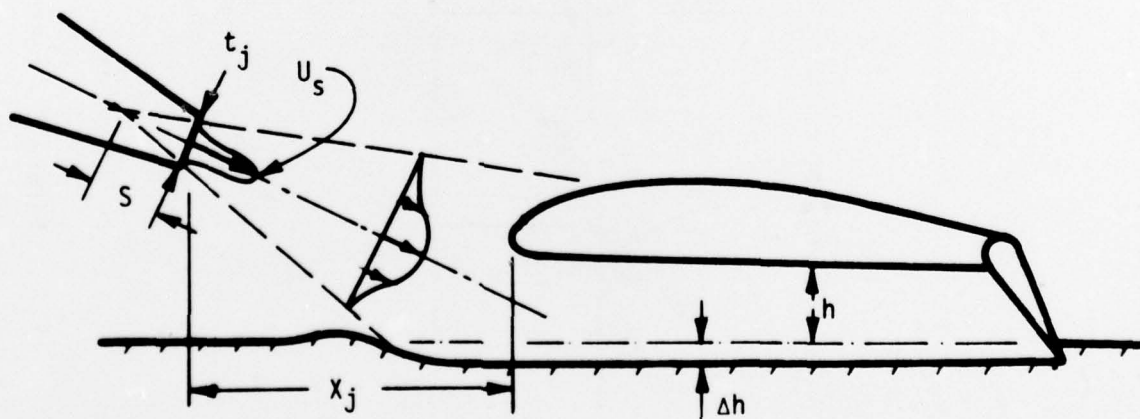
Figure 3 - Under-Wing Pressure Recovery versus X_j/h
(Conditions as Shown)

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MISTY
SPRAY

SHEAR SPRAY

DISCRETE
DROPLETS

PRESSURE SPRAY
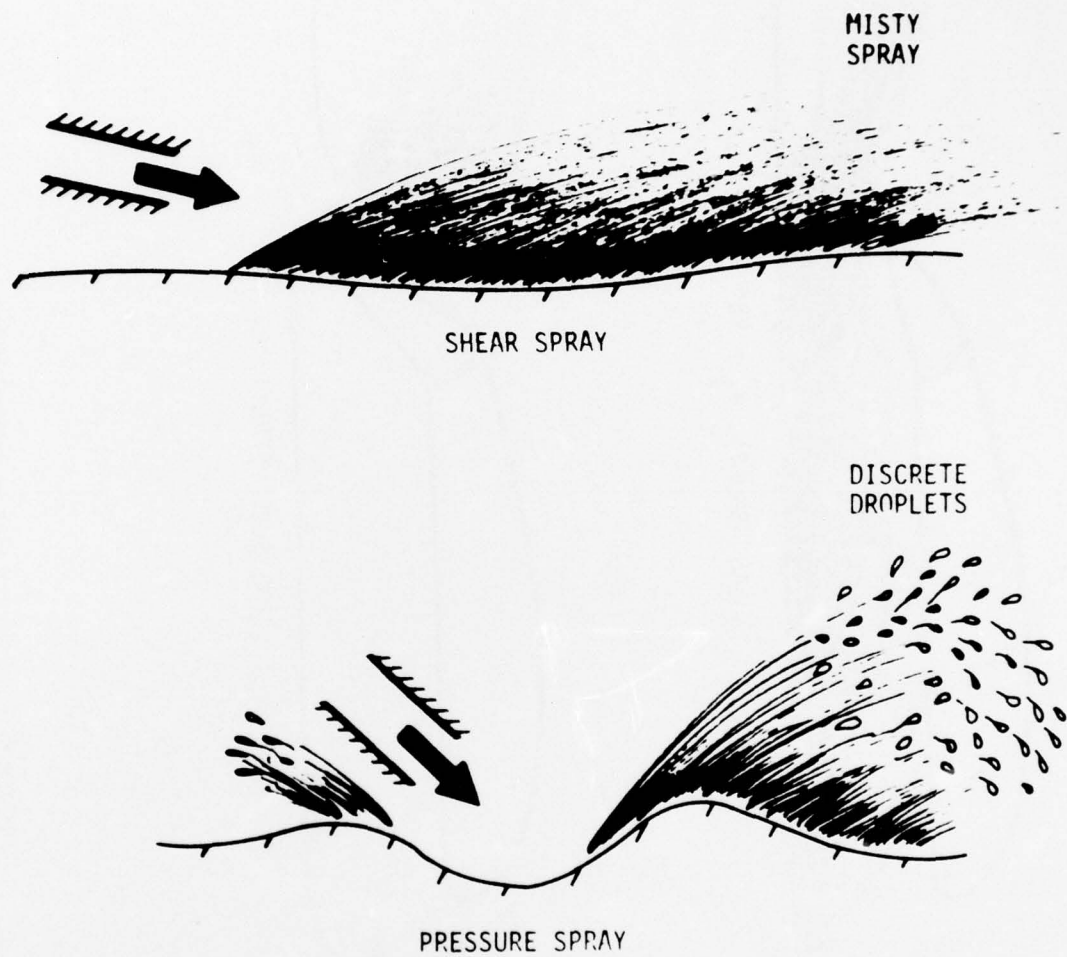
Figure 4 - Type of Spray Production
Dependence on Jet Impingement Angle

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$h_f/h \approx 1$ ("SHEAR" SPRAY), $\theta_j = 25°$

$h_f/h \ll 1$ ("PRESSURE" SPRAY), $\theta_j = 25°$
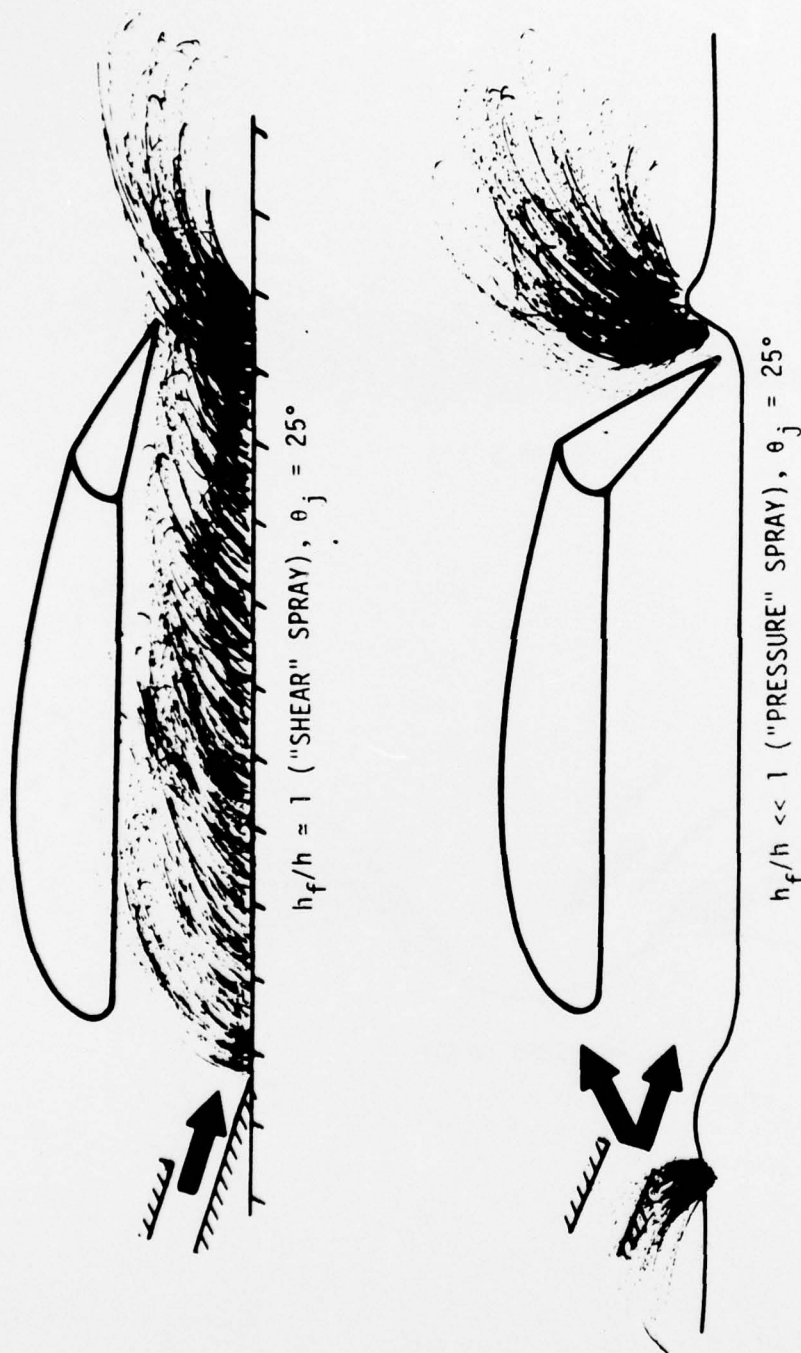
Figure 5 - Observed Spray Formation

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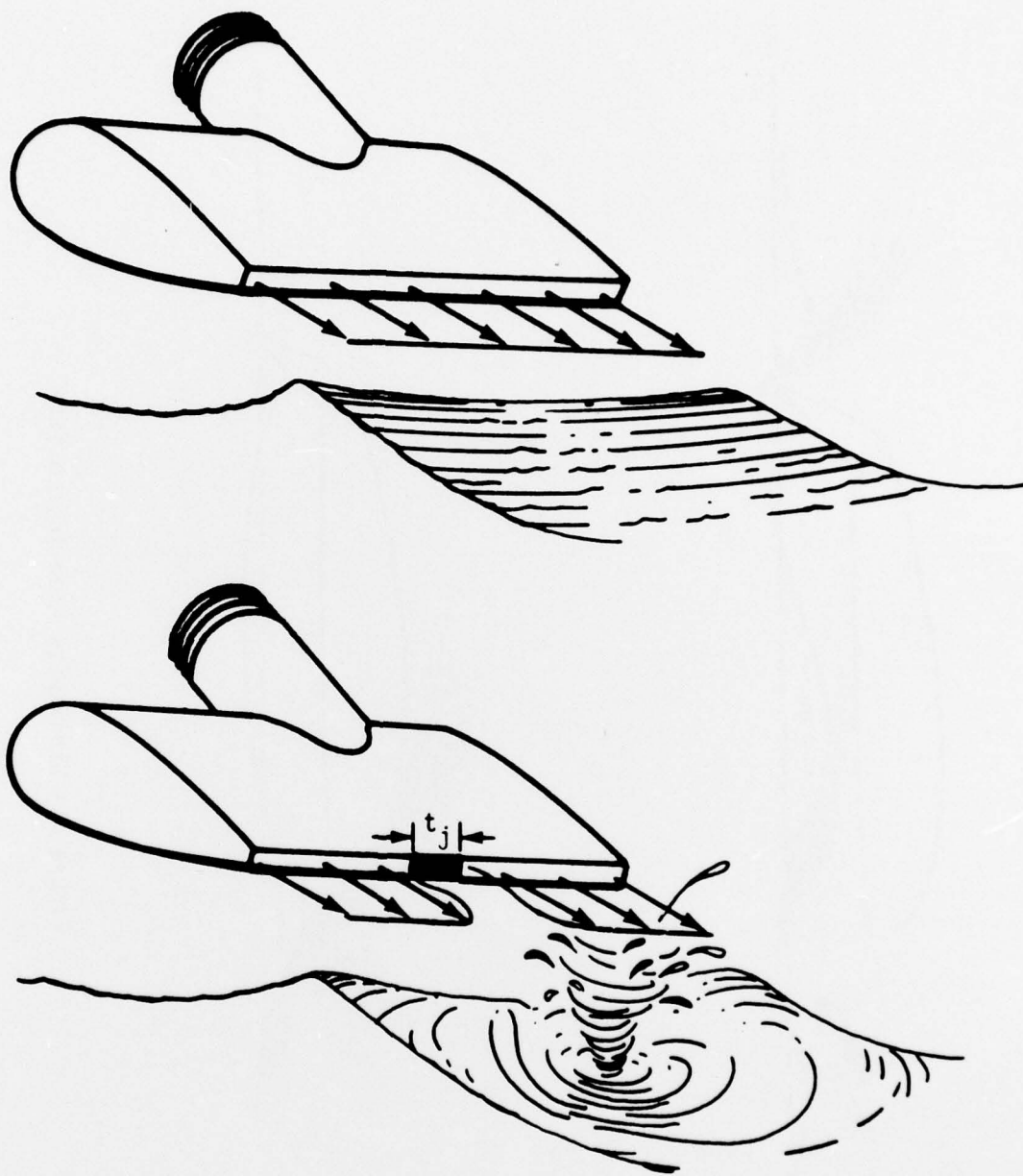
Figure 6 - Vortex Spray Induced by Lateral Jet Mixing

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Figure 7 - Streamwise Flow Instability
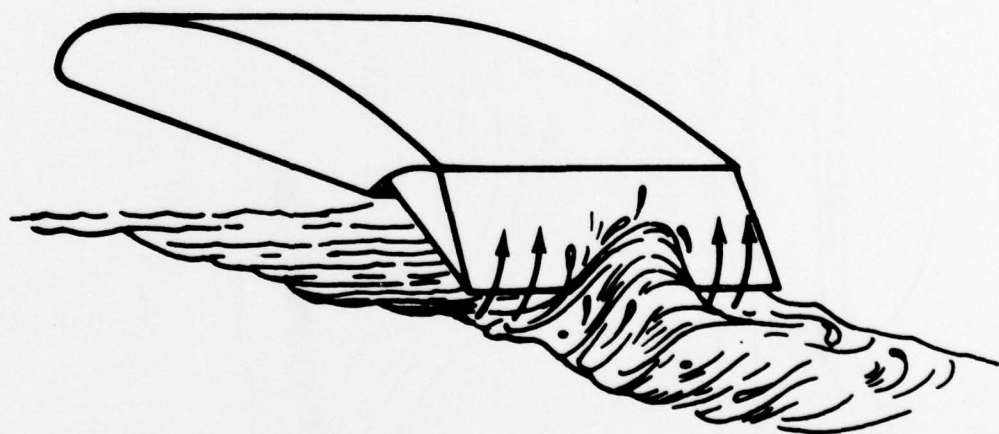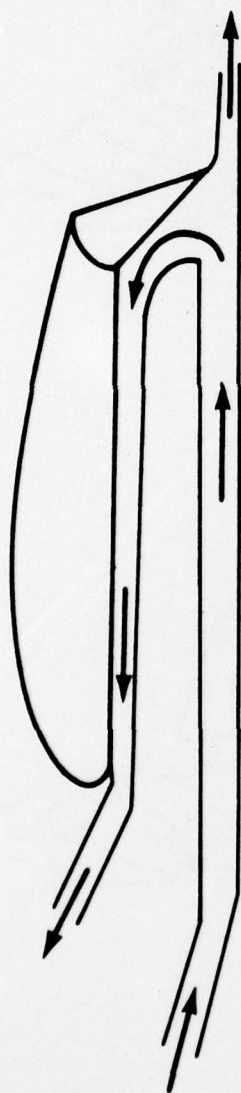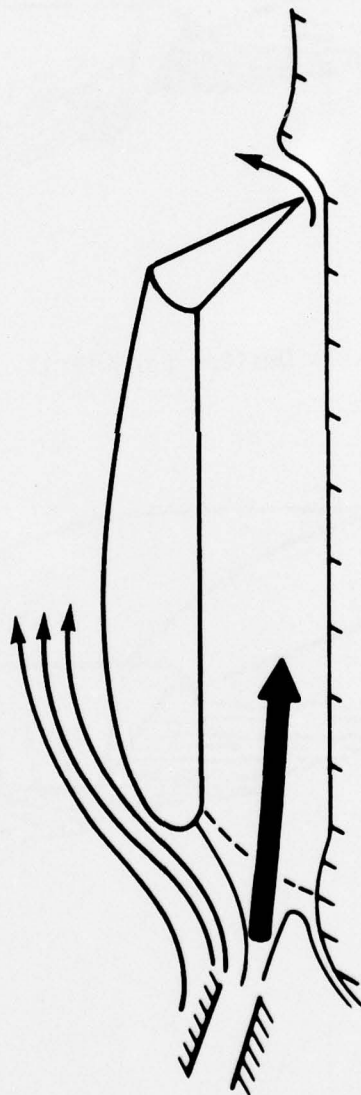
24
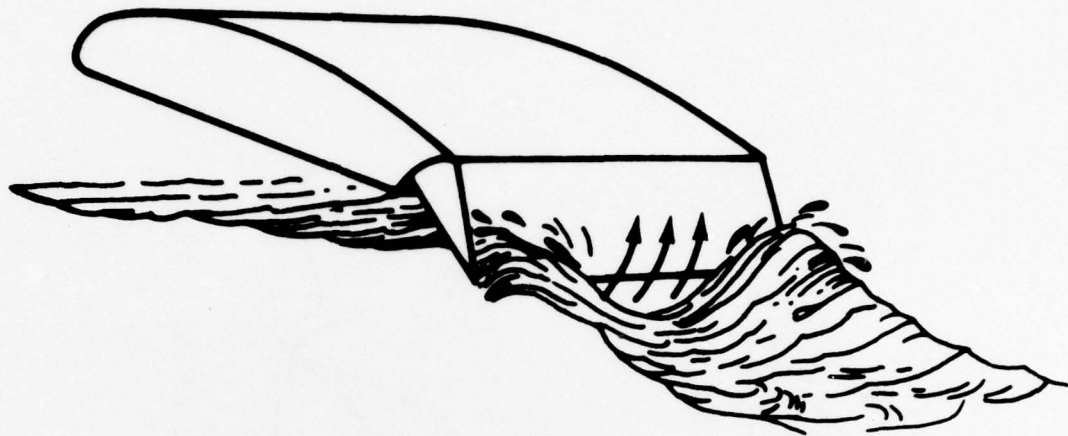
Note: Sidewalls Omitted For Clarity

Figure 8 - Cross-Stream Trailing Edge
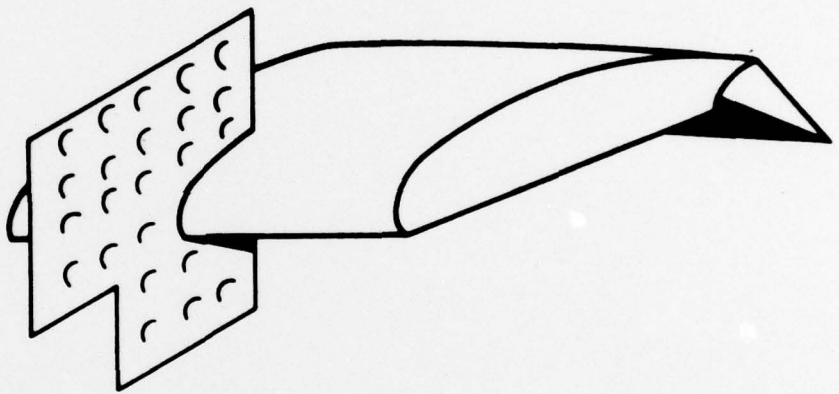Flow Instability, $h_f/\bar{q} = -2$

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THEORETICAL (INVISCID) SOLUTION FOR THIN JET, $h_f/t_j < 1$, SOLID SURFACE (REF 2)

ACTUAL (OBSERVED) FLOWFIELD FOR THIN JET, $h_f/t_j < 1$, WATER SURFACE (BASED UPON TUFT GRID STUDIES)

Figure 3 - Thrust Reversal Study

CUTOUT TO
ACCOMMODATE
JET EXIT

Figure 10 - Centerline Leading Edge Tuft Plate

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